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SEDIMENT YIELD AT SPANISH RESERVOIRS AND ITS RELATIONSHIP WITH THE DRAINAGE BASIN AREA (*)

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1. INTRODUCTION

The sediment yield is formally defined according to Vanoni (1975), as the total sediment outflow from a drainage basin or catchment area, measurable at a cross-section of reference and in a specified period of time. It is normally expressed in weight per surface unit and in time (t km^{-2} yr^{-1}).

Of the variety of procedures that are applied to determine the sediment yield in a catchment area, the one which is most widely accepted, is that which considers the sediment that has been deposited in a reservoir in a period of time (ICOLD, 1989). This methodology is very exact but

(*) *Apports solides dans les réservoirs espagnols et leur relation avec la surface du bassin versant.*

laborious, because both bathymetric and sedimentological techniques have to be used, as well as the calculation of different parameters: source, sediment grain-size and density, management system and reservoir trap efficiency, etc. It is beyond the scope of this paper to deal with the methodology in greater depth, because it has been explained in detail by Avendaño *et al.* (1995 a). The method was used to determine the sediment yield values in sixty Spanish catchment areas.

2. STUDY CATCHMENTS

The sixty reservoirs studied lie in 9 different river basins controlled by their 9 respective River Authorities, the distribution being as follows (Fig. 1): 3 in the Douro Basin, 6 in the Tagus Basin, 3 in the Guadiana Basin, 16 in the Guadalquivir Basin, 9 in the Segura Basin, 3 in the Sur Basin (Southern), 10 in the Júcar Basin, 9 in the Ebro Basin and 1 in the Pirineo Oriental (Eastern Pyrenees). The map in Fig. 1, shows the geographical position of these basins.

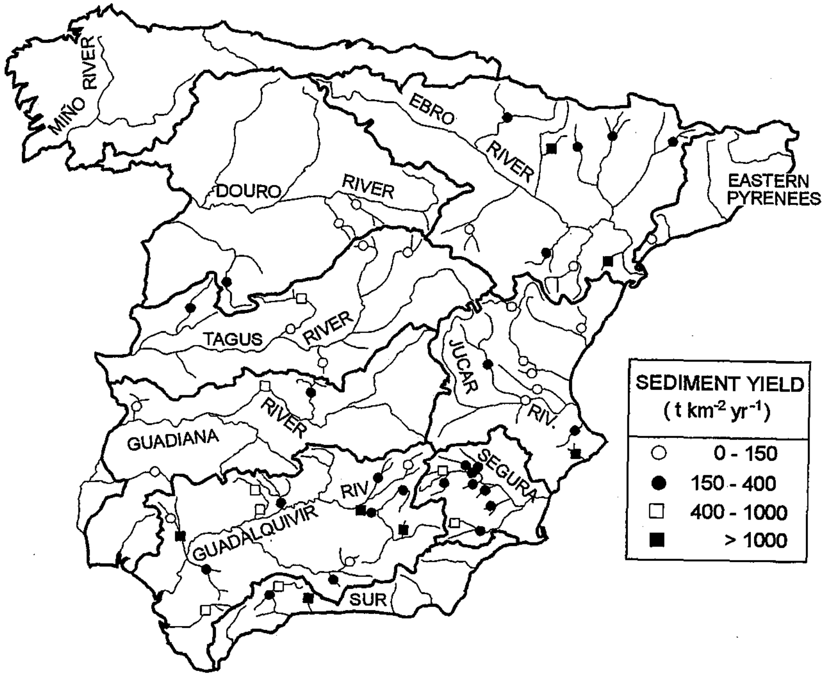

Fig. 1

Location and specific sediment yield of the catchments studied

Situation et taux spécifique d'apports solides dans les bassins versants étudiés

TABLE 1

List of the reservoirs studied, rivers basins to which they belong, and surface data, specific sediment yield (S.S.Y.) and sediment yield (S.Y.)

Liste des réservoirs étudiés, avec indication des bassins fluviaux auxquels ils appartiennent, des surfaces des bassins versants, des taux spécifiques d'apports solides (S.S.Y.) et des taux d'apports solides (S.Y.)

RESERVOIR	RIVER BASIN	AREA (km^2)	S.S.Y. (t km^{-2}yr^{-1})	S.Y. (t yr^{-1})
La Tranquera	Ebro	1,870	8.4	15,708
Embarcaderos	Júcar	16,952	17	288,184
Santolea	Ebro	1,221	18	21,978
María Cristina	Júcar	1,334	40	53,360
Guadalmena	Guadalquivir	1,350	46	62,100
Benageber	Júcar	3,495	54	188,730
Arquillo de San Blas	Júcar	690	59	40,710
Buseo	Júcar	220	64	14,080
Cazalegas	Tagus	1,955	70	136,850
El Vado	Tagus	379	72	27,288
Valuengo	Guadiana	1,156	73	84,388
Bembezar	Guadalquivir	1,665	97	160,027
Forata	Júcar	1,058	109	115,322
Riudecañas	Eastern Pyrenees	31	112	3,472
Pálmaces	Tagus	275	120	33,000
Burgomillodo	Douro	800	122	97,600
Cubillas	Guadalquivir	737	127	93,599
Linares del Arroyo	Douro	760	127	96,520
Guajaraz	Tagus	375	144	54,000
La Minilla	Guadalquivir	965	153	147,645
Cueva Forada	Ebro	644	176	113,256
Tranco de Beas	Guadalquivir	550	179	98,450
Argos	Júcar	444	198	87,912
Puentes	Segura	1,042	202	210,484
Santa María de Belsué	Ebro	190	216	41,040
Cenajo	Segura	1,060	220	233,200
Talave	Segura	763	246	187,698
Oliana	Ebro	2,694	246	662,724
Guadalmellato	Guadalquivir	1,195	252	301,140
La Cierva	Segura	167	279	46,593
Bermejales	Guadalquivir	300	280	84,000
Alfonso XIII	Segura	852	290	247,080
Torre del Aguila	Guadalquivir	439	296	129,944
Doña Aldonza	Guadalquivir	3,766	303	1,141,098
Camarillas	Segura	579	316	182,964
Contreras	Júcar	2,344	320	750,080
Santa Teresa	Douro	1,858	338	628,004
Gabriel y Galán	Tagus	1,846	345	636,870
Barasona	Ebro	1,250	350	437,500
Beniarrés	Júcar	469	357	167,433
Guadalén	Guadalquivir	1,281	359	459,879
Torre de Abraham	Guadiana	761	364	277,004
Taibilla	Segura	380	386	146,680
Yesa	Ebro	2,181	386	841,866
Guadalhorce	Sur	965	397	383,105
Bornos	Guadalquivir	1,361	448	609,728
Valdeinfierno	Segura	311	480	149,280
Puente Nuevo	Guadalquivir	559	516	288,444
La Breña	Guadalquivir	465	537	249,705
Conde de Guadalhorce	Sur	268	613	164,284
Fuensanta	Segura	1,201	682	819,082
Cijara	Guadiana	7,456	711	5,301,216
San Juan	Tagus	863	965	832,795
Sotonera	Ebro	323	1,121	362,083
Pena	Ebro	64	1,293	82,752
La Bolera	Guadalquivir	187	1,415	264,605
El Gergal	Guadalquivir	220	1,441	317,020
Viñuela	Sur	117	1,946	227,682
Pedro Marín	Guadalquivir	420	2,050	861,000
Guadalest	Júcar	60	2,703	162,180

The size of the drainage basins ranges from 31 km^2 (Riudecañas) to 16 952 km^2 (Embarcaderos). The total surface area covered by the sixty drainage basins is 79 173 km^2, which amounts to approximately 15 % of Spanish territory. The surface area occupied by the catchments within their respective river basins, ranges from 0.1 % in the Pirineo Oriental (Eastern Pyrenees) to 64 % in the Júcar Basin (Table 2). The number of years that these reservoirs have been operating, ranges from 5 (El Gergal reservoir) to 101 years (Puentes reservoir) but, in most cases, sediment records exist for several decades.

TABLE 2

Percentage of surface area studied for each of the river basins

Pourcentage de la surface étudiée pour chaque bassin fluvial

River Basin	Surface Area of River Basin (km^2)	Surface Area Studied (km^2)	Territory Covered (%)
Douro	77 500	3 418	4
Tagus	55 770	5 693	10
Guadiana	55 070	9 373	17
Guadalquivir	57 260	15 450	27
Sur (South)	18 380	1 350	7
Segura	18 735	6 356	34
Júcar	42 340	27 066	64
Ebro	84 840	10 436	12
Eastern Pyrenees	16 490	31	0.18

3. SPECIFIC SEDIMENT YIELD RESULTS

Table 1 shows the sediment yields (SY) and the specific sediment yield values (SSY) that were obtained in the 60 reservoir catchments studied. The specific sediment yield values in these drainage basins are extremely diverse, ranging from 8.4 to 2 703 t km^{-2} yr^{-1}, these extreme figures being for the Tranquera and Guadalest reservoirs, respectively. The average specific sediment yield as a whole, amounts to 429 t km^{-2} yr^{-1}. Given the diversity of the specific sediment yield, 3 groups of catchments have been established, on the basis of their specific sediment yield values. These are as follows:

Group 1. – Catchments with a low specific sediment yield (less than 150 t km^2 yr^{-1}). This group consists of 20 catchments, lying either in zones where the erosion processes are not very marked (ICONA, 1988), or in zones where carbonate lithologies predominate, in which chemical erosion, not quantifiable with the procedure used, is greater than physical erosion. The latter aspect basically holds for the Júcar Basin.

Group 2. – Catchments with an intermediate specific sediment yield (ranging from 150 and 1 000 t $km^{-2}yr^{-1}$). This is the largest group, containing over 50 % of the reservoirs studied (33).

Group 3. – Catchments with a high specific sediment yield (greater than 1 000 t km^{-2} yr^{-1}). This group includes 7 basins, which are characterised by their smallness (less than 420 km^2 in all cases), this being a feature that is conducive to the eroded sediment in the catchment area being transported down into the reservoir.

The distribution of the specific sediment yield values per river basin shows considerable divergence (Table 3, Fig. 1). It can be observed that there is a relatively narrow range of specific sediment yield values in the Júcar and Segura Basins, that goes from 202 to 682 t km^{-2} yr^{-1} in the Segura basin, and from 17 to 357 t km^2 yr^{-1} in the Júcar basin, if the figures for the Guadalest reservoir are excluded. The values are extremely inconsistent for the rest of the river basins. It should be pointed out, that the highest average specific sediment yield values are for the Sur (South) and the Guadalquivir Basins (Table 3).

TABLE 3

Minimum, maximum and average specific sediment yield values (S.S.Y.) in the river basins studied

Valeurs minimale, maximale et moyenne des taux spécifiques d'apports solides (S.S.Y.) dans les bassins fluviaux étudiés

River Basin	Minimum S.S.Y. (t $km^{-2}yr^{-1}$)	Maximum S.S.Y. (t $km^{-2}yr^{-1}$)	Average S.S.Y. (t $km^{-2}yr^{-1}$)
Douro	122	338	195
Tagus	70	965	266
Guadiana	73	711	382
Guadalquivir	46	2 050	522
Sur (South)	397	1 946	985
Segura	202	682	344
Júcar	17	2 703	435
Ebro	8.4	1 293	423

4. RELATIONSHIP BETWEEN SEDIMENT YIELD TO RESERVOIRS AND THE DRAINAGE BASIN AREA

Several authors have identified that a relationship exists between sediment yield and the drainage basin area, in the sense that the more extensive the surface area to be drained the greater the yield (e.g. Milliman and Syvitski, 1992; Romero Díaz *et al.*, 1992; Wasson, 1994, etc.). The statistical studies carried out for the purposes of this paper, reveal that the existence of such a relationship is endorsed in the Spanish catchments studied. Such a relationship becomes all the more apparent, if we consider separately the three groups of basins described in section 3 (Fig. 2).

The potential-type mathematical function is the one that best defines the relationship between the two variables. The function characteristics for each of the three groups of catchments concerned can be seen in Table 4. The correlation coefficients can be considered satisfactory in all three groups. However, given the small amount of data (7) available for Group 3, the equation must be taken with reservations. The best

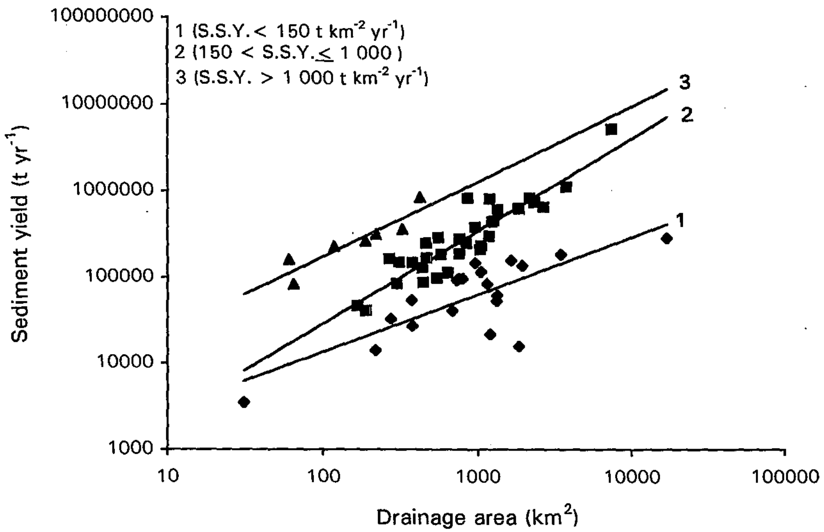

Fig. 2

Regression lines that relate the catchment surface area to the sediment yield for the three groups

Lignes de régression dans la relation entre la surface du bassin versant et le taux d'apports solides pour les trois groupes

coefficients were obtained for Group 2, which can be regarded as representative of the average situation in Spain, given that it includes the largest number of catchments.

TABLE 4

Regression equations that define the relationship between sediment yield (S.Y., t/year) and the drainage basin area (A, km^2) for each of the three groups

Équations de régression définissant la relation entre la quantité d'apports solides (S.Y., t/a) et la surface A du bassin versant (km^2) pour chacun des trois groupes

Group	S.S.Y. (t/km^2/year)	Equation	r	n
1	< 150	$S.Y = 617A^{0.67}$	0.77	20
2	150 - 1 000	$S.Y = 202A^{1.07}$	0.92	33
3	> 1 000	$S.Y = 3\,137A^{0.87}$	0.91	7

5. SEDIMENT DELIVERY RATIO

The sediment transported by the drainage network to the reservoirs only constitute a small part of the gross erosion that takes place in the catchment area, given that a considerable amount of eroded material is deposited elsewhere, before reaching the point of reference. The fraction or percentage of the total sediment eroded, which is transported outside a basin or specific area, is referred to as the sediment delivery ratio (SDR) (Glymph, 1954) and can be expressed as SDR = SY/GE, where GE is the gross erosion, SY, the sediment yield.

The gross erosion data is taken to be that determined by ICONA (1988) using the Universal Soil Loss Equation, together with the sediment yield values that are presented in this work (Table 1), the sediment delivery ratios have been determined for 37 of the catchment areas studied. A wide variation of delivery ratios are obtained, ranging from 0.8 % (María Cristina) to 67.47 % (El Gergal). However, most of the reservoirs studied (27) are characterised by delivery ratios below 25 %, which is a percentage considered normal for large river (ASCE, 1975). The wide range of sediment delivery ratio values obtained, is due to the fact that both the erosion values and the specific sediment yield vary greatly from one catchment to another. Thus, catchments with the lowest specific sediment yield values, are not always those with the lowest erosion rates and, likewise, the highest specific sediment yield values are not necessarily to be found in the catchments with the highest erosion rates (Fig. 3).

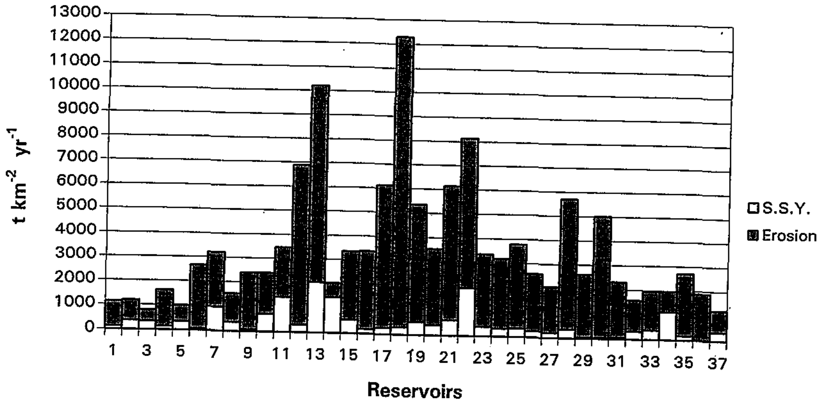

Fig. 3

Comparison between the average erosion and specific sediment yield values for the 37 catchment areas studied

Comparaison entre l'érosion moyenne et la valeur du taux spécifique d'apports solides pour les 37 bassins versants étudiés

Many geomorphological and environmental factors, such as the nature, surface area and location of the sediment source zone, together with the relief, slope, transport system, vegetation cover, etc., affect the delivery ratio (Singh, 1989). The predominant factor is the drainage basin area (Walling, 1983).

Different researchers (e.g., Maner, 1958; Roehl, 1962; etc.) have used some of these parameters to draw up empirical equations for predicting the sediment delivery ratios with which to calculate the sediment yield for a catchment for which the erosion rate is known or can be determined.

Along these lines, the authors have, by statistical analysis, attempted to obtain an empirical equation to predict the sediment delivery ratio value in Spanish catchments, using the following variables: the drainage basin area, the slope of the main rivers and the weighted bifurcation ratio (Avendaño *et al.,* 1995 b). However, it has not yet been possible to establish a correlation between these variables and the sediment delivery ratio. So, at present, it can only be stated that the drainage basin area clearly affects the sediment delivery ratio. This factor does not exert the same influence on all catchments, there being four main groups (Fig. 4). The catchments with high specific sediment yields, are generally

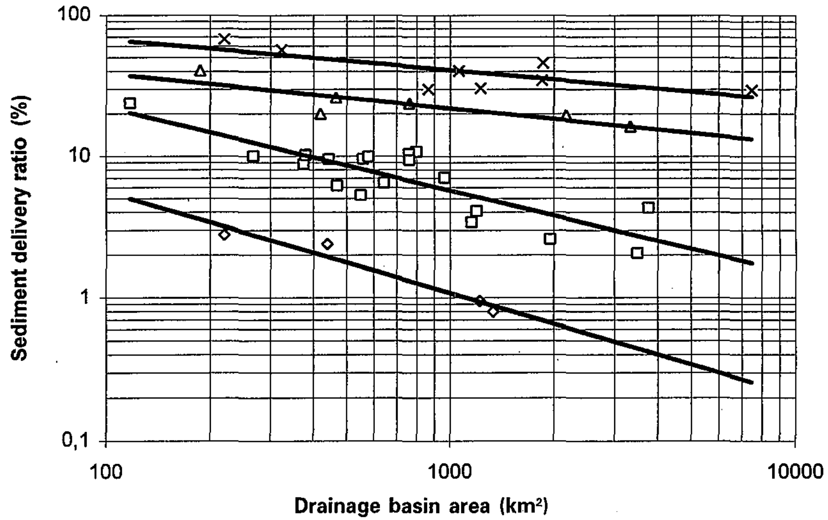

Fig. 4

Relationship between the drainage basin areas (km²) and the sediment delivery ratios (%)

Relation entre les surfaces (km²) des bassins versants et les proportions de débits solides (%)

characterised by high delivery ratios, i.e. with efficient delivery systems, and the catchments with the lowest specific sediment yield values have the lowest delivery ratios. As is the case when the catchment surface area is correlated with the sediment yields, the optimum correlation coefficients were obtained for the group with an intermediate delivery ratio, which shows that the drainage basin area for the reservoirs in this group can serve for prediction purposes. Another series of parameters, yet to be determined, affects the remaining catchments areas, and these will have to be studied in detail.

CONCLUSIONS

In the sixty catchments analysed, a relationship exists between the sediment yield at the reservoirs and the surface area covered by the former. However, the same type of relationship is not common to all, there being three groups, distinguished on the basis of their specific sediment yield (low, < 150 t km^{-2} yr^{-1}; intermediate, from 150 to 1 000 t km^{-2} yr^{-1}, or high, $> 1\,000$ t km^{-2} yr^{-1}). Most of the catchments studied fall into the intermediate specific yield group, and thus these must be taken as being representative of the Spanish average. Although the variables that affect the degree of specific yield in a catchment have yet to be determined, it can nevertheless be said that the mathematical model established, once the drainage basin area is known, makes it possible to predict the sediment yields to the reservoirs, within a well defined variation interval.

Another way of predicting the sediment yield to reservoirs, involves applying a mathematical model for the sediment delivery ratio. It has been established that the catchment surface area is also the major factor affecting the sediment delivery ratio for Spanish reservoirs.

The surface area covered, has been used to distinguish different groups of catchments, both on the basis of the specific yield and the delivery ratio. Research into the factors that cause these differences will probably provide greater insight into the erosion processes and the means for applying corrective measures in each case.

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SUMMARY

One of the most widely accepted methods for accurately estimating the average erosion in catchment areas, consists of quantifying the sediment deposited in their downstream lakes and reservoirs. This method was applied to estimate the average erosion rates and sediment yield in sixty drainage basins, whose areas cover 15 % of the Spanish territory. The specific sediment yield in the catchments studied ranges from 8 to 2 703 t km^{-2} yr^{-1}. The average figure for the sixty catchments is 429 t km^{-2} yr^{-1}. The highest sediment yield values are for the basins situated in southern Spain (Southern Basin and the Guadalquivir Basin).

A close relationship has also been established between the sediment yields and the drainage basin areas, the larger this area, the greater the

sediment yield. Furthermore, the mathematical model that defines this relationship has also been determined and it is suggested that it be used for prediction purposes.

RÉSUMÉ

Une des méthodes les plus largement acceptées pour estimer avec précision l'érosion moyenne dans un bassin versant consiste à quantifier les sédiments déposés dans les lacs et réservoirs à l'aval. Cette méthode a été appliquée pour évaluer les taux moyens d'érosion et les apports solides dans soixante bassins versants, dont les surfaces représentent 15 % du territoire espagnol. L'apport spécifique de sédiments dans les bassins étudiés varie de 8 à 2 703 t/km^2/an. La valeur moyenne pour les soixante bassins est de 429 t/km^2/an. Les valeurs les plus élevées d'apports solides sont celles des bassins situés au sud de l'Espagne (le bassin du Sud et le bassin du fleuve Guadalquivir).

On a établi une relation entre les apports solides et les surfaces des bassins versants; plus cette surface est grande, plus les apports solides sont élevés. En outre, un modèle mathématique qui définit cette relation a été établi et il est suggéré de l'utiliser pour effectuer des prévisions.